Statistical Entry, Descent, and Landing Performance Reconstruction of Mars Science Laboratory

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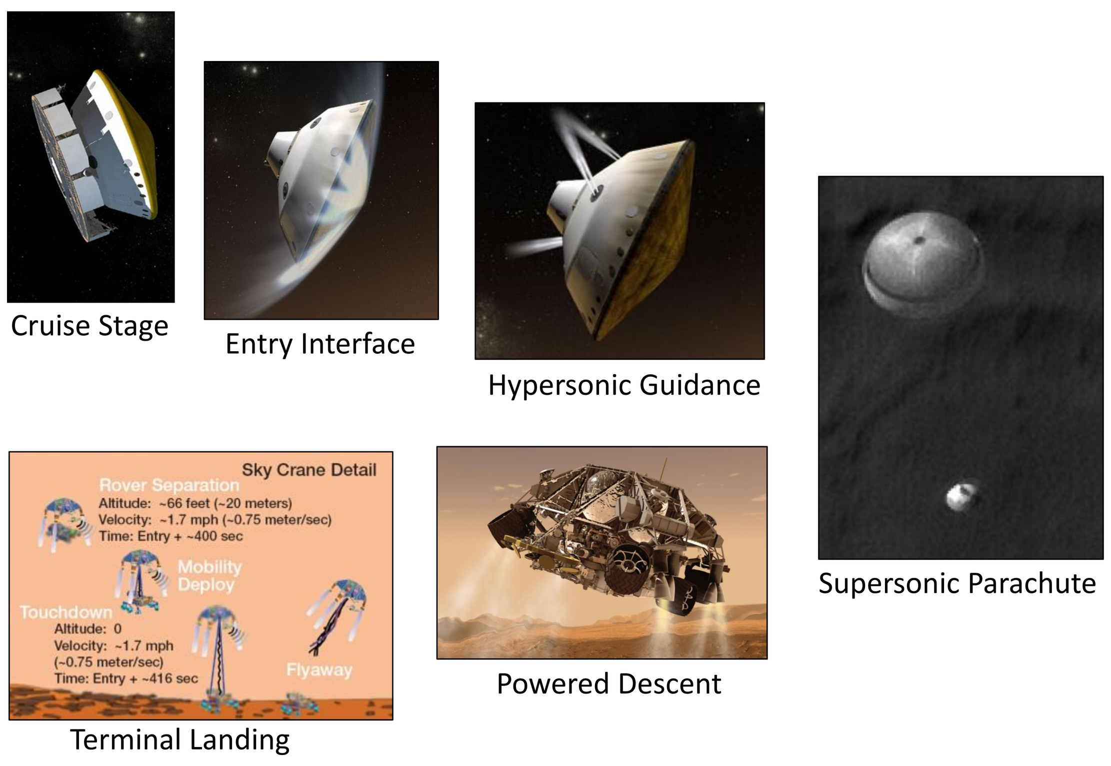
MSL EDL Concept of Operations



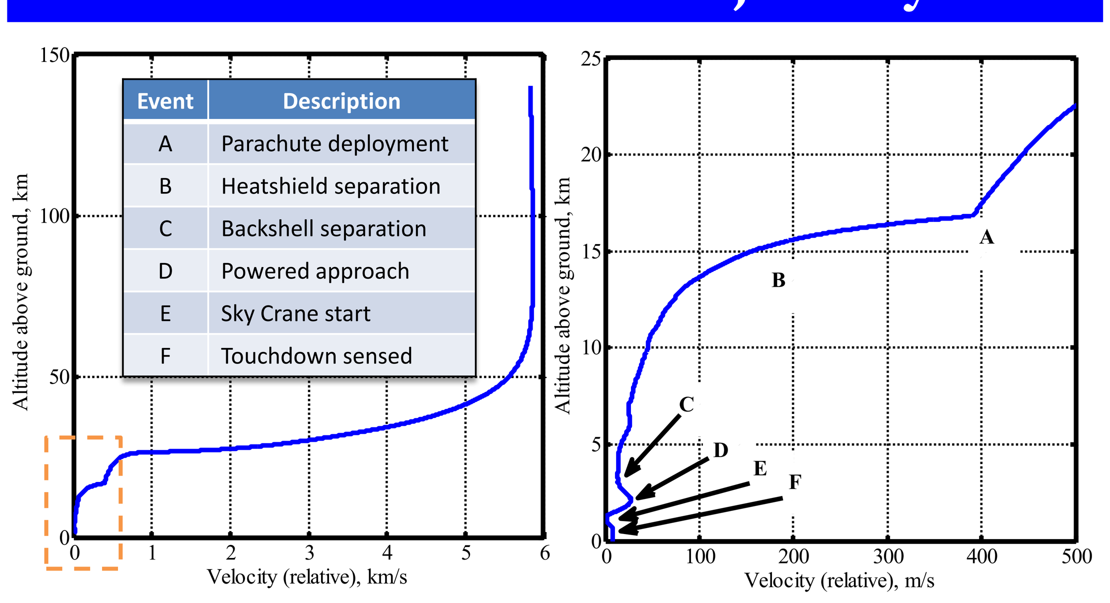
MSL landed in Gale Crater on Mars on August 5th, 2012 after a 10 month interplanetary journey. The payload, the Curiosity rover, was the largest payload for a planetary mission, and MSL flew the largest aeroshell and the largest supersonic parachute. MSL also completed hypersonic guidance using bank angle reversals and used the innovative Sky Crane system to gently place the payload on the ground.

States	Initial Conditions	3σ (normal)*
Radius (centric), m	3522200	32.066
Latitude (centric), deg.	-3.91865	0.000781
Longitude, deg.	126.718	0.000367
Velocity (inertial), m/s	6083.33	0.026059
Azimuth angle (inertial), deg.	93.2064	0.000268
Flight-path angle (inertial) deg.	-15.4892	0.000400

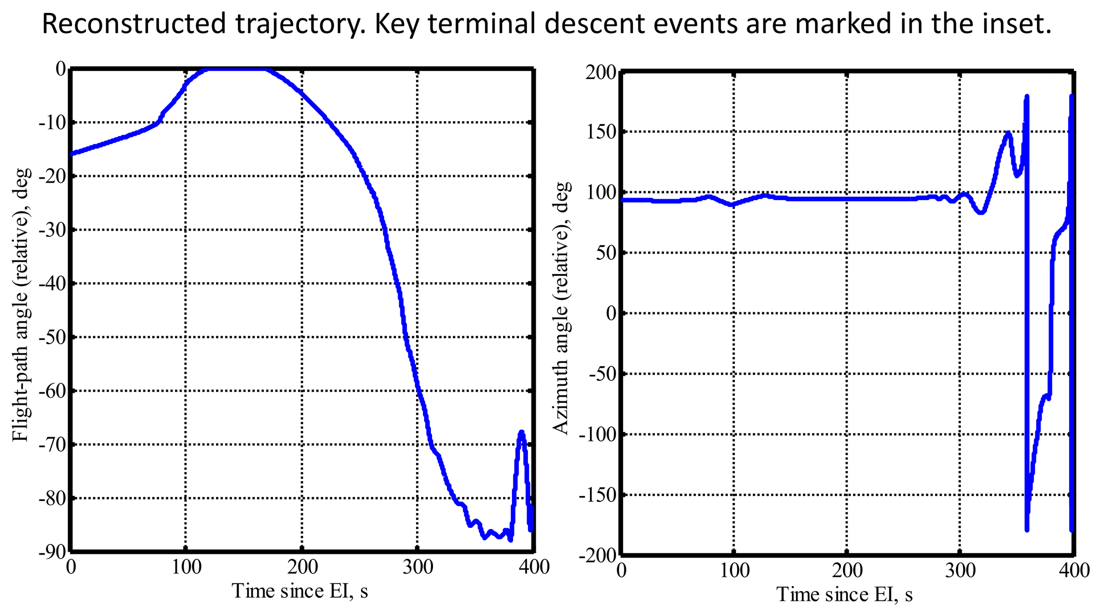
* Calculated using Monte Carlo simulation starting from covariance at EI – 9 minutes

Data	Time used in analysis	Hz
Accelerometer	EI to ground	200
Angular rates	EI to ground	200
MEADS	~49 s to 175 s (q_∞ ≥ 850 Pa)	8
Radar altimeter	290 s to ground	1

Reconstructed Trajectory



Reconstructed trajectory. Key terminal descent events are marked in the inset.

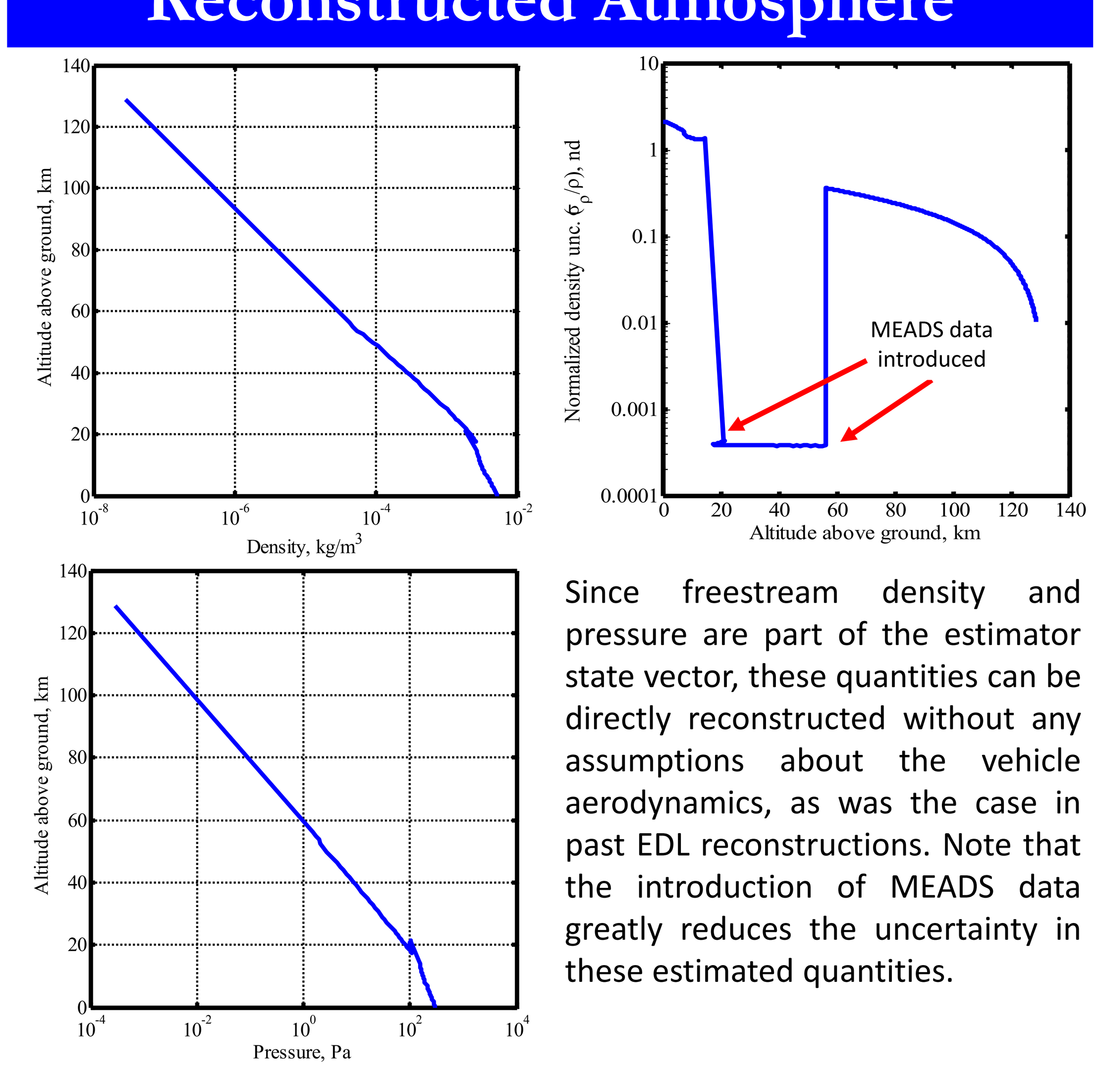


Comparison of Actual and Reconstructed Landing Location

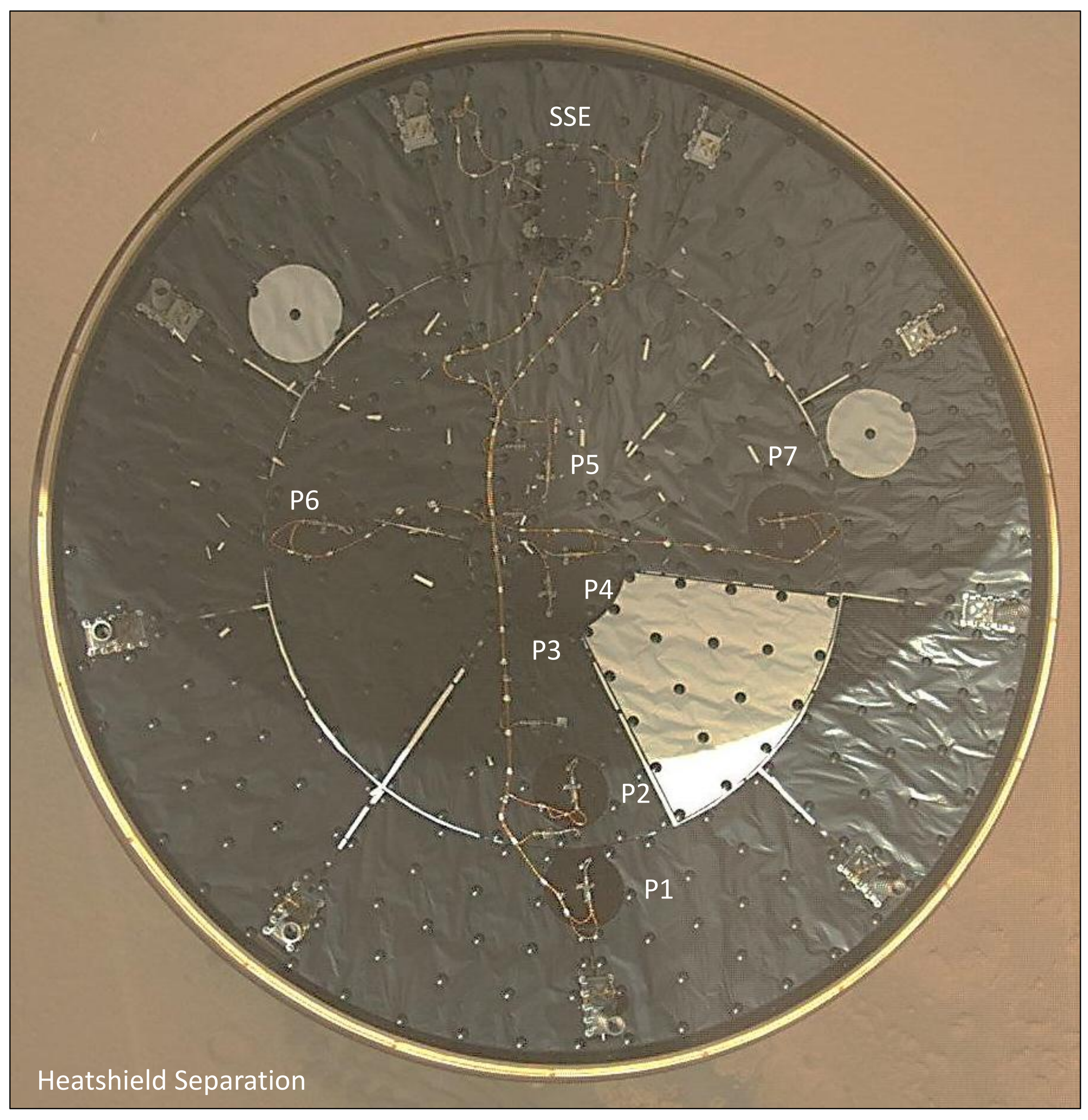
Position State	Actual†	Estimated	3σ (normal)
Radius (centric), km	3391.134	3390.741	0.6048
Latitude (centric), deg.	-4.5965	-4.6322	0.0752
Longitude (East), deg.	137.4019	137.3940	0.0264

† Based on post-flight communication between rover and orbiting satellites.

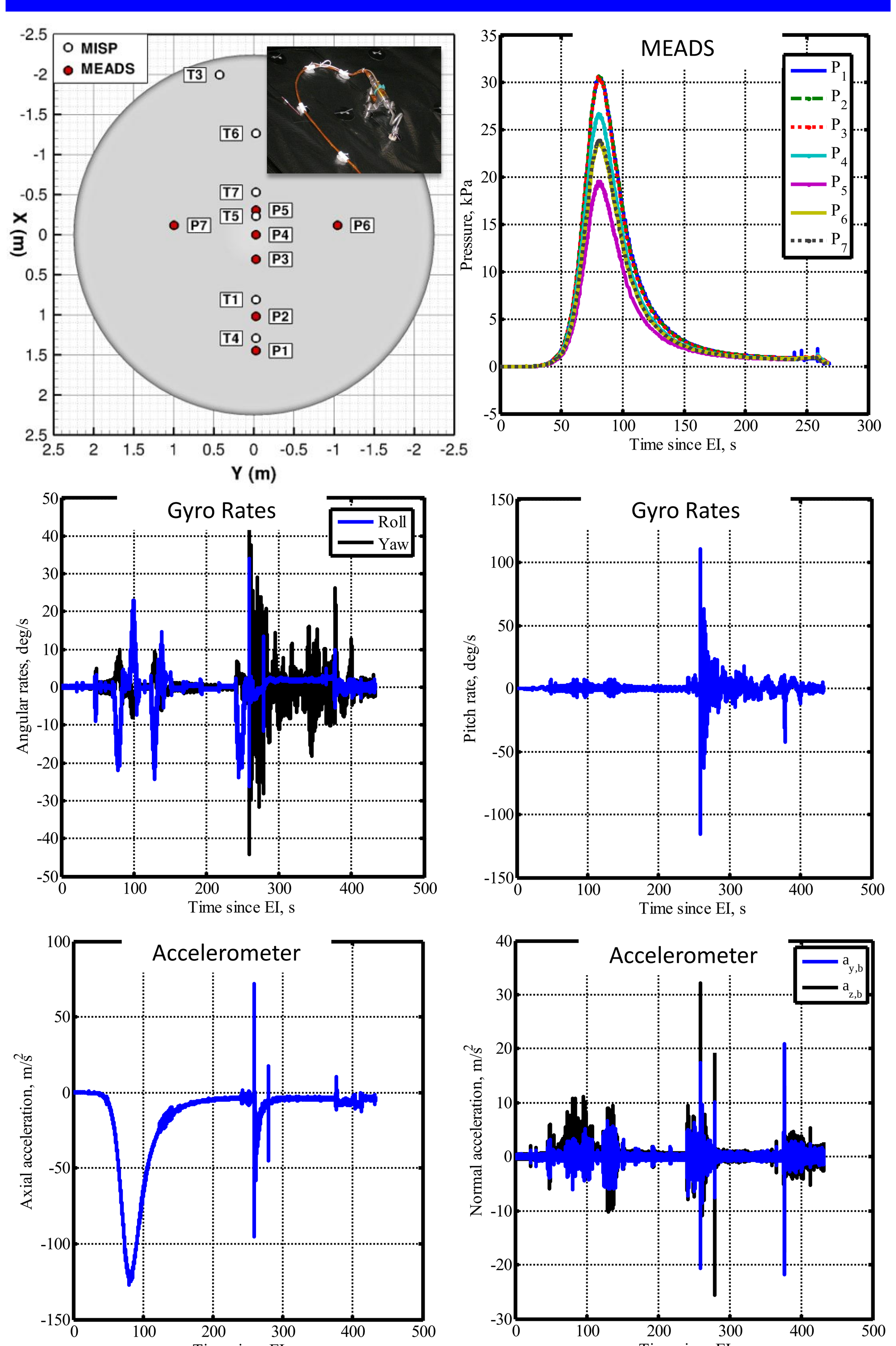
Reconstructed Atmosphere



Since freestream density and pressure are part of the estimator state vector, these quantities can be directly reconstructed without any assumptions about the vehicle aerodynamics, as was the case in past EDL reconstructions. Note that the introduction of MEADS data greatly reduces the uncertainty in these estimated quantities.

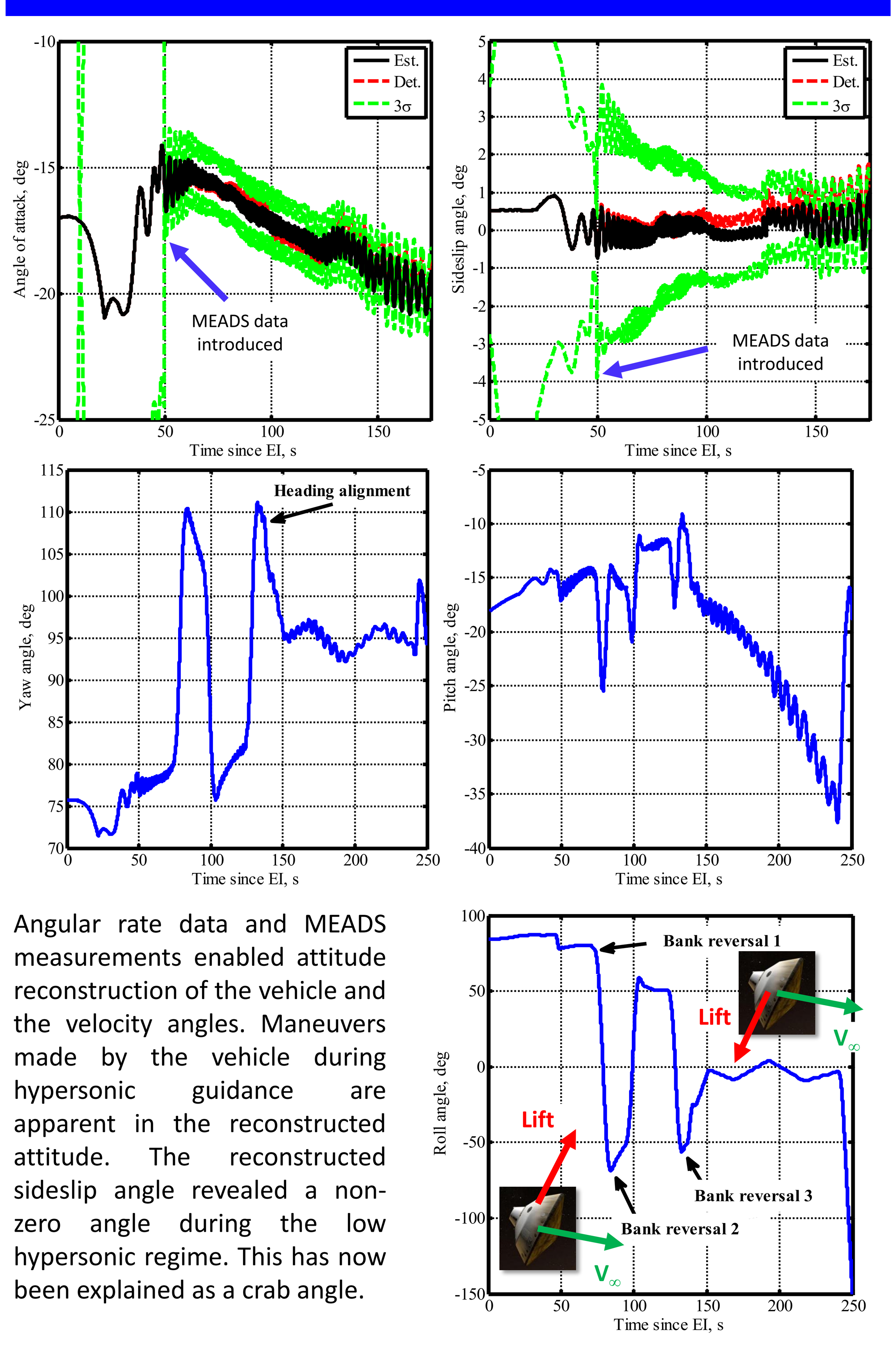


MSL Instruments and Data



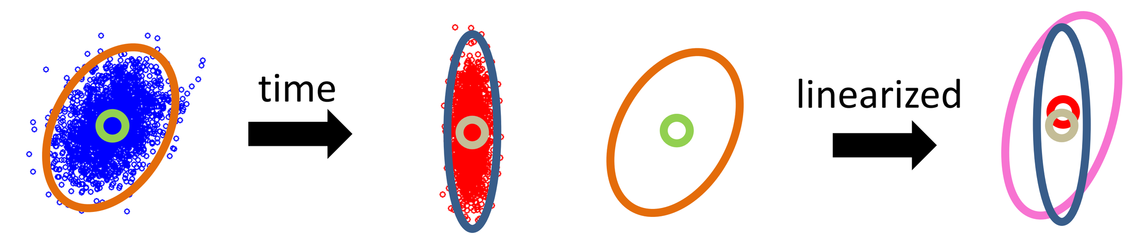
Radar altimeter data (range and range rate) were also used for the reconstruction but the data are not shown here.

Attitude Reconstruction



Angular rate data and MEADS measurements enabled attitude reconstruction of the vehicle and the velocity angles. Maneuvers made by the vehicle during hypersonic guidance are apparent in the reconstructed attitude. The reconstructed sideslip angle revealed a non-zero angle during the low hypersonic regime. This has now been explained as a crab angle.

Statistical Estimation Methods

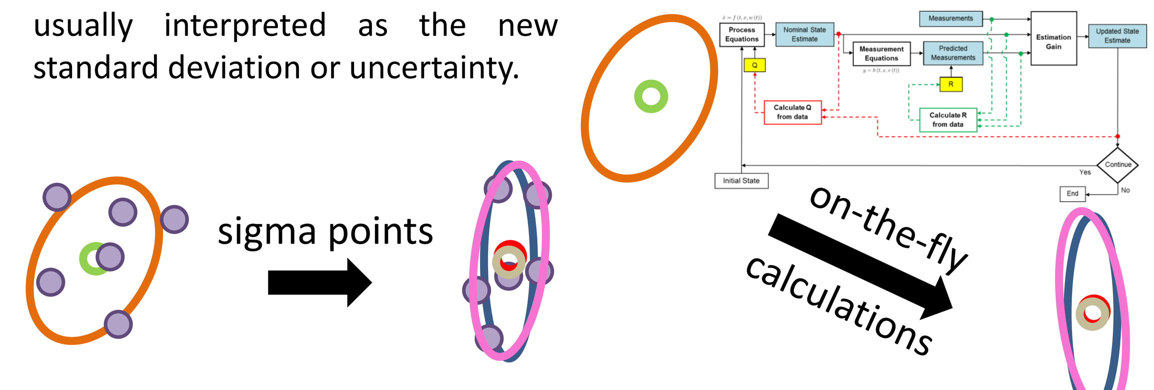


Actual Process

The estimate of the state is uncertain and can be described by a distribution with a **mean** and a **variance**. As the distribution evolves in time, the **mean**, **variance**, and the shape of the distribution changes. The new **mean** is interpreted as the new value of the state, while the square-root of the new **variance** is usually interpreted as the new standard deviation or uncertainty.

Extended Kalman Filter

EKF linearizes certain parts of the non-linear, actual process to propagate the state and uncertainty in time. EKF is great with estimation of the new **mean** but the linearization leads to a less accurate **variance** and uncertainty estimate. EKF assumes states have a normal distribution.



Unscented Kalman Filter

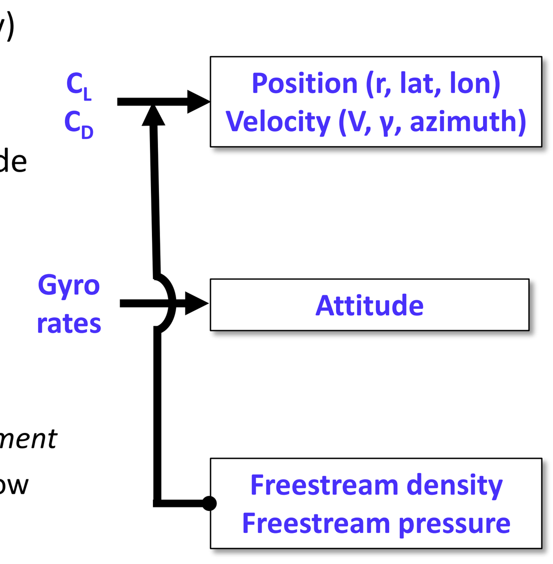
UKF uses specially chosen values called **sigma points** to sample the distribution. These points are propagated through the non-linear process and the new mean and variance are calculated. UKF estimates the mean and uncertainty better and is computationally more intensive than the EKF.

Adaptive Filter

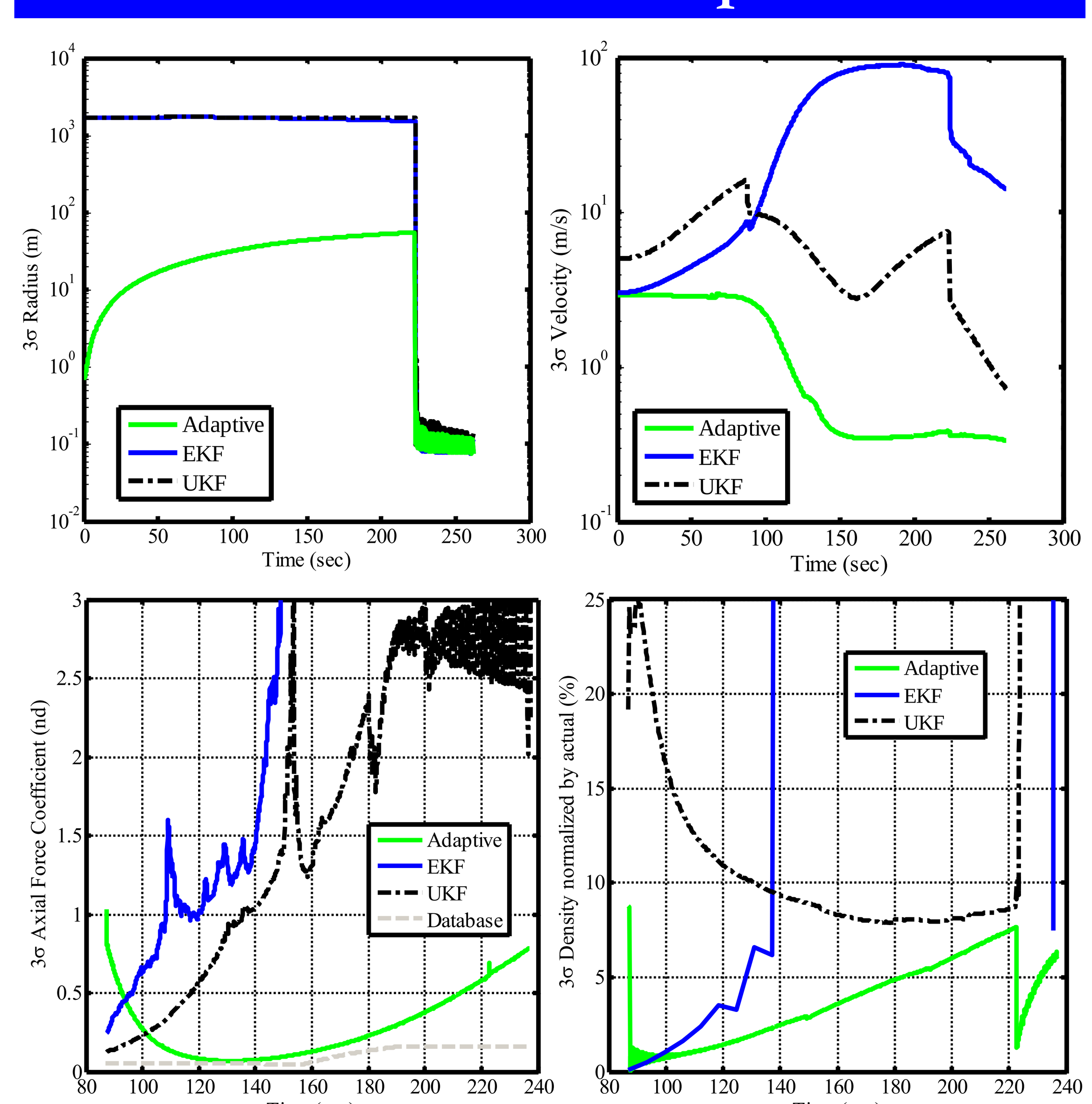
EKF and UKF assume *a priori* knowledge of process and measurement noise uncertainty. This is usually an incorrect assumption for many dynamical systems, such as Mars EDL. Adaptive filter calculates these noises on-the-fly, improving both mean and uncertainty estimates.

Difference from Other Estimations

- Equations of motion (position, velocity) use aerodynamic and atmospheric parameters
- Angular rate data integrated for attitude state quaternion
- Dynamic hydrostatic and perfect gas equation for pressure and density
- Velocity equations <u>do not</u> need accelerometer data
  - Treats accelerometer data as *measurement*
  - Both accelerometer and MEADS can now *observe* freestream density



Possible Estimation Improvements



The reconstruction results provided for MSL were conducted using the EKF. The authors plan to use UKF and Adaptive filters for MSL reconstruction (see paper in the reference). However, in lieu of MSL results, the plots above show the effects of using UKF and Adaptive filter with simulated MSL data.

Although the EKF and UKF show good accuracy in general, the Adaptive filter has much tighter confidence bounds, demonstrated in the reconstructed uncertainties of the radius and velocity of the vehicle.

The tighter confidence bounds of the Adaptive filter can be leveraged to improve models used for design, such as the aerodynamics database or atmospheric predictions. Although these are results from simulated data, the figures show that flight data could be used to improve uncertainty quantification of these models.

Acknowledgements

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Further Discussion

1. Dutta, S., Braun, R.D., Russell, R.P., Striepe, S.A., and Clark, I.G., "Comparison of Statistical Estimation Techniques for Mars Entry, Descent, and Landing Reconstruction," *Journal of Spacecraft and Rockets*, Vol. 50, No. 4 (printed online on May 2013).
2. Dutta, S., Braun, R.D, and Karlgaard, C.D., "Uncertainty Quantification for Mars Entry, Descent, and Landing Reconstruction Using Adaptive Filtering," AIAA 2013-0026, *51st Aerospace Sciences Meeting*, Grapevine, TX, January 2013.
3. Dutta, S. and Braun, R.D., "Statistical Entry, Descent, and Landing Performance of Mars Science Laboratory," *AIAA SciTech 2014 Conference*, National Harbor, MD (submitted).